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**ONE-FIFTH-SCALE FUEL ELEMENT
COLUMN SHAKE TEST
FINAL REPORT**

by
J. FISCHER, J. E. RAKOWSKI, and B. E. OLSEN

**Prepared under
Contract DE-AT03-76ET35300
for the San Francisco Operations Office
Department of Energy**

DATE PUBLISHED: SEPTEMBER 1979

GENERAL ATOMIC COMPANY

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ABSTRACT

A series of seismic tests were performed on a one-fifth-scale HTGR fuel element column. The column was subjected to static deflections, free vibrations, and uniaxial and biaxial horizontal and vertical sinusoidal and earthquake time history excitations. Main parameters measured were column displacements and element impact forces, dowel forces, and rocking angles.

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1. SUMMARY AND CONCLUSIONS

The following paragraphs summarize the more important results obtained from all phases of the test program.

The static deflection tests recorded column deflections under statically applied lateral forces and in-plane moments.

The column pluck tests recorded the short-term transient response of the column in free vibration by releasing the column from a statically deflected configuration. In this mode of vibration a resonance frequency of 3.5 Hz and viscous damping of 15% of critical were estimated for an initial deflection of 0.010 in. The resonance frequency decreased with increasing deflections, which shows that the unconstrained column structure represents a spring-softening system.

The data recorded for uniaxial, horizontal sine sweep excitation of the column showed that impact with the test fixture boundary occurred at all test g-levels. In this mode of excitation, the lateral resonance frequency of the column increased with an increase in the excitation g-level, a phenomenon which is characteristic of a nonlinear spring-hardening system. At 0.5 g fixture acceleration, the resonance frequency was 8.8 Hz.

The fundamental vertical column resonance frequency at 0.5 g was measured to be 29 Hz. This resonance was verified by calculation considering the column as a lumped mass on a spring. The calculation showed that the resonance was attributable to the support post structure. Analysis of sweep-up and sweep-down resonance curves clearly indicated a nonlinear spring-softening system.

Additional peaks in the frequency response curves indicate other resonance frequencies at 17, 25, 27, and 34 Hz. Analysis of the test rig and shaker table accelerometer data has shown these resonances to be shaker table structural resonances typically caused by loosening of the mono-ball joints and shaker oil column flexibility.

The biaxial sine sweep test data showed the same resonance frequencies as recorded in the uniaxial tests; however, the response magnitudes of several peaks were intensified by the coupled motion.

The uniaxial time history tests illustrated that the column support post loads during horizontal excitation were significantly higher than those achieved during vertical excitation. This result seems to be attributable to the column support block gap, which largely affects post loads. A change in the support block gap changes both the local loading and the load at remote points in the column, presumably through a change in the mode shape of vibration.

Biaxial tests were performed while varying the input excitation g-level, phase lag, and column gap. It was found that maximum response occurs for horizontal and vertical input applied in-phase and that the vertical input has little effect on lateral column response quantities such as element impact forces and dowel forces. Also, increasing the column gap largely increased the element lateral impact forces and dowel forces, as did an increase in the excitation g-level.

Although all instrumentation functioned adequately and instrument random errors were small, large errors in the computed dowel forces and element collision forces resulted, since these forces were extremely sensitive to small geometrical misalignments of the elements and the individual boundary support pads.

2. INTRODUCTION

The one-fifth scale fuel element column shake test was conducted to provide an understanding of fuel element column behavior when subjected to horizontal and vertical excitation and to provide data for correlation with the single core column analytical model, COCO, prior to its expansion into a multi-column version. The test scope included frequency response tests with sinusoidal input and time history tests employing synthesized earthquakes. The frequency response tests were used to study the core column horizontal and vertical resonance characteristics. The horizontal time history input was the GAC design earthquake (shock 4) used earlier in the one-fifth scale dowel force test, since this shock produced the largest model response. The vertical time history input was the associated vertical component of shock 4, represented at the core support floor elevation.

The most important aspect of the single-column seismic test was the input of simultaneous horizontal and vertical excitation to the model. Of particular interest was the measurement of response quantities such as dowel forces, element rocking forces, and element vertical separations.

These tests were performed at Wyle Laboratories, Norco, California, during the period of March through August, 1975 (Ref. 1).

3. TEST OBJECTIVES

The test objective was to obtain static and dynamic response data from an instrumented one-fifth scale HTGR fuel element column. The column response quantities obtained as a function of column elevation, input g-level, boundary gap, and column end constraints were the following:

1. Horizontal and vertical resonance frequencies and mode shapes.
2. Column damping during free transient decay.
3. Horizontal and vertical boundary support forces.
4. Interelement dowel forces.
5. Interelement vertical (rocking) forces.
6. Interelement vertical separations and rocking angles.
7. Fuel element velocities.

4. MODEL AND TEST RIG DESCRIPTION

4.1. MODEL DESCRIPTION

The test column is shown in Fig. 4-1. It consisted of 14 individual elements of graphite stacked one on top of another to make one single column 78 in. high. The elements were one-fifth-scale models of the prototype hexagonal fuel element.* Of the 14 elements, 11 were full-length (6.24 in.) and three were half-length (3.12 in.).

There was no vertical constraint between elements other than their weight. Lateral constraint between blocks was provided by the three dowel pins at each interface. Additional details of the model elements and the assembled column are presented in report (a) of Ref. 2.

During the static tests and pluck tests, the blocks were numbered from bottom to top, 1 through 14. For the shaker tests the elements were rearranged to place the instrumented elements at a higher position in the column.

To expedite the testing, the elements employed were taken from previously completed tests such as the one-fifth-scale full-array and used without modification (Ref. 3). Table 4-1 lists the source of the elements in the model. Since the actual element widths, and clearances in the dowel system, were required as input to the analytical models, these data were measured and recorded by the test lab and entered into the test data packages.

*The scaling relationships for the elements are discussed in Ref. 3.

Fig. 4-1. Fifth scale test column

TABLE 4-1
SOURCE OF TEST BLOCKS

Element No.	Static and Pluck Tests	Shaker Tests
14	470-1 from DFT ^(a)	New
13	1 from BRT ^(b)	No. 11 in Static and Pluck
12	New	Unchanged
11	4-10 from DFT	New
10	2 from BRT	New
9	7-4 from DFT	Unchanged
8	New	Unchanged
7	3 from BRT	Unchanged
6	4 from BRT	Unchanged
5	New	Unchanged
4	New	Unchanged
3	New	Unchanged
2	1-7 from DFT	New
1	4-9 from DFT	New

(a) DFT - Dowel Force Test (Ref. 3).

(b) BRT - Basic Rocking Test (Ref. 4).

During sine sweep and time history testing of the model, the column rested on four spring support posts having a net spring rate of 3400 lb/in. This stiffness resulted in the scaled fundamental vertical frequency of a prototype core fuel region.

4.2. TEST RIG DESCRIPTION - STATIC AND PLUCK TESTS

The test column was installed in a fixture (Fig. 4-2) consisting of two welded box beams joined at the bottom by a thick steel plate that was in turn welded to the floor. At the top was a thick machined spacer plate bolted between the fixture columns. Thus, the test column was framed by the fixture. The right-hand side of the fixture contained 14 supports spaced vertically along the beam so that each support was aligned with each graphite element in the test column. The support consisted of a horizontal threaded shaft with an aluminum plate at the end attached normal to the shaft. This plate was faced with a sheet of graphite and was used to simulate a neighboring element. The supports were instrumented and measured the element impact forces with the boundary. The shafts passing through the fixture beam were adjustable in a horizontal direction and were locked in place with jam nuts.

Provisions were made for displacing the test column toward the left fixture column by means of a pull hoop that slipped around the elements but made contact only on the corners. A nylon monofilament line and pulley system was attached to the pull hoop. For the static deflection tests, known weights were hung on the line. For the pluck tests the line was attached to a turn screw on the left fixture beam and was wound up until the desired column initial lateral displacement was achieved.

The top and base elements in the column were constrained from rotation by boundary plates on both the left- and right-hand sides. The boundary plates on the upper element were set to a 0.005-in. total clearance to assure that the element was free to move vertically while being constrained

Fig. 4-2. Fixture assembly for the static pulse and column pluck tests

in rotation. The constraint of the upper element varied during the static deflection tests and is defined in Section 6.1.

4.3. TEST RIG DESCRIPTION - SINE SWEEP AND TIME HISTORY TESTS

The test rig supporting the column during the sine sweep and time history tests is shown in Fig. 4-3. It utilized the same fixture used in the static and pluck tests. The fixture was lowered into the table as shown in the figure so that the overturning moment could be kept to a minimum. Details of the part of test rig below the table are shown in Fig. 4-4.

Fig. 4-3. Setup and fixture assembly for the sine sweep and time history tests

Fig. 4-4. Fixture assembly for sine sweep and time history tests (below shaker table)

5. INSTRUMENTATION

5.1. INSTRUMENTATION PLAN

Table 5-1 gives the instrumentation used in the static deflection and pluck phases of the testing. Figure 5-1 shows the location and type of instrumentation.

Table 5-2 gives the instrumentation used in the sine sweep and time history phases of the testing, while Fig. 5-2 shows the location and type of instrumentation.

The following physical events were measured:

1. Lateral displacement of the column. The position of the column relative to the boundary support was measured. For the static and pluck tests, these measurements included the initial and final position of each element, measured at the bottom of each element for the static tests and at the top and bottom of each element for the pluck tests. LVDTs were also used to measure the center position of the elements at levels 3 and 7 during their motion in the pluck tests.

For the shake tests, LVDTs were placed at element levels 1, 3, 7, and 14 to measure the lateral motion.

2. Impact load of the column against the boundary.

For the pluck tests, the impact of element 7 against the boundary was measured.

TABLE 5-1
PLUCK TEST INSTRUMENT IDENTIFICATION

Word	Instrument/Measurement	Location	Measure- ment Number	Wyle S/N	Equip. Rack to Comp. Room	F-2 Boom
1						
2						
3						
4						
5						
6						
7						
8						
9	Block sep. B-2-2 ECP	Section 2-3	BS02	W7307	35	35
10	Block sep. B-2-1 ECP	Section 2-3	BS02	W7308	36	36
11	Block sep. 6/7-2 ECP	Section 6-7	BS06	W7314	37	37
12	Block sep. 6/7-1 ECP	Section 6-7	BS06	W7313	38	38
13	Block sep. 10/11-2 ECP	Section 10-11	BS10	W7316	39	39
14	Block sep. 10/11-1 ECP	Section 10-11	BS10	W7332	40	40
15						
16						
17						
18	Block 7(X) displ. LVDT	Rig. el. 07	BDX 07	W45220	22	22
19	Block 3(X) displ. LVDT	Rig. el. 03	BDX03	W45240	23	23
20						

TABLE 5-1 (continued)

Word	Instrument/Measurement	Location	Measure- ment Number	Wyle S/N	Equip. Rack to Comp. Room	F-2 Boom
21						
22						
23						
24						
25						
26						
27						
28						
29	Block sep. B-2-2 ECP	Section 2-3	BS02	W7307	35	35
30	Block sep. B-2-1 ECP	Section 2-3	BS02	W7308	36	36
31	Block sep. 6/7-2 ECP	Section 6-7	BS06	W7314	37	37
32	Block sep. 6/7-1 ECP	Section 6-7	BS06	W7313	38	38
33	Block sep. 10/11-2 ECP	Section 10-11	BS10	W7316	39	39
34	Block sep. 10/11-1 ECP	Section 10-11	BS10	W7332	40	40
35						
36						
37						
38	Block 7(X) displ. LVDT	Rig. el. 07	BDX07	W45220	22	22
39	Block 3(X) displ. LVDT	Rig. el. 03	BDX03	W45240	23	23
40						

TABLE 5-1 (continued)

Word	Instrument/Measurement	Location	Measure- ment Number	Wyle S/N	Equip. Rack to Comp. Room	F-2 Boom
41	Mid-height X-1 2 9031	Rig. el. 07	BFX07	7395, 7394	53/68/(a)	53
42						
43						
44						
45						
46	Block sep. B-2-2 ECP Block sep. B-2-1 ECP Block sep. 6/7-2 ECP Block sep. 6/7-1 ECP Block sep. 10/11-2 ECP Block sep. 10/11-1 ECP	Section 2-3 Section 2-3 Section 6-7 Section 6-7 Section 10-11 Section 10-11	BS02 BS02 BS06 BS06 BS10 BS10	W7307 W7308 W7314 W7313 W7316 W7332	35 36 37 38 39 40	35 36 37 38 39 40
47						
48						
49						
50						
51						
52						
53						
54	Block 7(X) displ. LVDT Block 3(X) displ. LVDT	Rig. el. 07 Rig. el. 03	BDX07 BDX03	W45220 W45240	22(a) 23	22 23
55						
56						
57						
58						
59						
60						

(a) Lines to be monitored on visicorder.

TABLE 5-1 (continued)

Word	Instrument/Measurement	Location	Measure- ment Number	Wyle S/N	Equip. Rack to Comp. Room	F-2 Boom
61						
62						
63	Rocking load 6-7(1) 9001	Section 6-7	RF07	7355,6	/76/(a)	
64	Rocking load 6-7(2) 9001	Section 6-7	RF07	7357,8	/77/(a)	
65	Dowel force 6-7 (ΣX)	Section 6-7	DF06	C(b)	4/78(a)	7,9,11
66	Dowel force 6-7 (ΣZ)	Section 6-7	DF06	D(c)	5/79	8,10,12
67						
68						
69	Block sep. B-2-2 ECP	Section 2-3	BS02	W7307	35	35
70	Block sep. B-2-1 ECP	Section 2-3	BS02	W7308	36	36
71	Block sep. 6/7-2 ECP	Section 6-7	BS06	W7314	37(a)	37
72	Block sep. 6/7-1 ECP	Section 6-7	BS06	W7313	38	38
73	Block Sep. 10/11-2 ECP	Section 10-11	BS10	W7316	39	39
74	Block sep. 10/11-1 ECP	Section 10-11	BS10	W7332	40	40
75						
76						
77						
78	Block 7(X) displ. LVDT	Rig. el. 07	BDX07	W45220	22	22
79	Block 3(X) displ. LVDT	Rig. el. 03	BDX03	W45240	23	23
80						

(a) Lines to be monitored on visicorder.

(b) C = W7421, W7423, W7419

(c) D = W7435, W7420, W7418

Fig. 5-1. Pluck test instrument configuration

TABLE 5-2
SINE SWEEP AND TIME HISTORY INSTRUMENTATION IDENTIFICATION

Word	Instrument/Measurement	Location	Measure- ment Number	Wyle S/N	Equip. Rack to Comp. Room	F-10 Line/ Boom
1	Fixture displ. (X) shaker LVDT	Horiz. shaker	TFDX		1(a)	
2	Fixture displ. (Y) shaker LVDT	Vert. shaker	TFDY		2(b)	
3	Support post (Y-1) 901A P(c)	Post X-1	SPFY1	W7468	/61	
4	Rig accelerometer (X) top	Rig top (X)	TFAX	W7300	4	
5	Rig accelerometer (Y) base	Rig base (Y)	TFAY	W7301	5	
6	Rig accelerometer (X) base	Rig base (X)	TFAX	W7398	6	
7	Fixture displ. (X)	Rig top	TFDX	W31685		
8	Support post (Y-2) 901A	Post X-2	SPFY2	W7327	60/81	60
9	Block sep. B-2-2 ECP	Base-2	BS01	W7315	35	35
10	Block sep. B-2-1 ECP	Base-2	BS01	W7312	36	36
11	Block sep. 10/11-2 ECP	Section 10-11	B10	W7314	37	37
12	Block sep. 10/11-1 ECP	Section 10-11	B10	W7313	38	38
13	Block sep. 13/14-2 ECP	Section 13-14	BS14	W7309	39	39
14	Block sep. 13/14-1 ECP	Section 13-14	BS14	W7311	40	40
15	Top block (Y) displ. ECP	Rig. el. 14	BDY14	W7331	41	41
16	Base block (Y) displ. ECP	Rig. el. 01	BDY01	W7310	42	42
17	Base block (X) displ. LVDT	Rig. el. 01	BDX01	W45202	21	21
18	Block 7 (X) displ. LVDT	Rig. el. 07	BDX07	W45220	22	22
19	Block 3 (X) displ. LVDT	Rig. el. 03	BDX03	W45240	23	23
20	Top block (X) displ. LVDT	Rig. el. 14	BDX14	W45241	24	24

(a) Lines to be monitored on visicorder.

(b) Line to be substituted for channel 71, line 37, during vertical excitation.

(c) P = Peak Holder Channel.

TABLE 5-2 (continued)

Word	Instrument/Measurement	Location	Measurement Number	Wyle S/N	Equip. Rack to Comp. Room	F-10 Line/Boom
21	DC frequency (X)	N/A	N/A		3	
22	DC frequency (Y1)	N/A	N/A		3	
23	U/A					
24	U/A					
25	Start/stop	N/A	N/A	N/A	7/27	N/A
26	Dowel force B-2 (Σ X) P(a)	El. 1-2	DF01	A(b)	83,63,13, 15,17	
27	Dowel force 13-14 (Σ X) P(a)	El. 13,14	DF13	B(c)	84,64,14, 16,18	
28	Support post (Y-2) 901A	Post X-2	SPFY2	W7327	60/81	60
29	Block sep. B-2-2 ECP	Base-2	BS01	W7315	35	35
30	Block sep. B-2-1 ECP	Base-2	BS01	W7312	36	36
31	Block sep. 10/11-2 ECP	Section 10-11	BS10	W7314	37	37
32	Block sep. 10/11-1 ECP	Section 10-11	BS10	W7313	38	38
33	Block sep. 13/14-2 ECP	Section 13-14	BS14	W7309	39	39
34	Block sep. 13/14-1 ECP	Section 13-14	BS14	W7311	40	40
35	Top block (Y) displ. ECP	Rig. el. 14	BDY14	W7331	41	41
36	Base block (Y) displ. ECP	Rig. el. 01	BDY01	W7310	42	42
37	Base block (X) displ. LVDT	Rig. el. 01	BDX01	W45202	21	21
38	Block 7 (X) displ. LVDT	Rig. el. 07	BDX07	W45220	22	22
39	Block 3 (X) displ. LVDT	Rig. el. 03	BDX03	W45240	23	23
40	Top block (X) displ. LVDT	Rig. el. 14	BDX14	W45241	24	24

(b)A = W7428, W7430, W7433

(c)B = W7429, W7432, W7434

(a)P = Peak Holder Channel

TABLE 5-2 (continued)

Word	Instrument/Measurement	Location	Measure- ment Number	Wyle S/N	Equip. Rack to Comp. Room	F-10 Line/ Boom
41	Base block X-1 Σ 2 903A P(a)	Rig. el. 1	BFX01	45513A,B	51/66	51
42	Base block X-2 Σ 2 903A P(a)	Rig. el. 1	BFX01	45511A,B	52/67	52
43	Mid-height X-1 Σ 2 903A P(a)	Rig. el. 7	BFX07	45512A,B	53/68(b)	53
44	Mid-height X-2 Σ 2 923A P(a)	Rig. el. 7	BFX07	7395,4	54/69(b)	54
45	Top block X-1 Σ 2 903A P(a)	Rig. el. 14	BFX14	45514A,B	55/70	55
46	Top block X-2 Σ 2 903A P(a)	Rig. el. 14	BFX14	45510A,B	56/71	56
47	Rocking load B-2-1 2 901 P(a)	Base-2	RF02	45524,5	57/72	57
48	Support post (Y-2) 901A	Post X-2	SPFY2	W7327	60/81	60
49	Block sep. B-2-2 ECP	Base-2	BS01	W7315	35	35
50	Block sep. B-2-1 ECP	Base-2	BS01	W7312	36	36
51	Block sep. 10/11-2 ECP	Section 10-11	BS10	W7314	37	37
52	Block sep. 10/11-1 ECP	Section 10-11	BS10	W7313	38	38
53	Block sep. 13/14-2 ECP	Section 13-14	BS14	W7309	39	39
54	Block sep. 13/14-1 ECP	Section 13-14	BS14	W7311	40	40
55	Top block (Y) displ. ECP	Rig. el. 14	BDY14	W7331	41	41
56	Base block (Y) displ. ECP	Rig. el. 01	BDY01	W7310	42	42
57	Base block (X) displ. LVDT	Rig. el. 01	BDX01	W45202	21	21
58	Block 7 (X) displ. LVDT	Rig. el. 07	BDX07	W45220	22(b)	22
59	Block 3 (X) displ. LVDT	Rig. el. 03	BDX03	W45240	23	23
60	Top block (X) displ. LVDT	Rig. el. 14	BDX14	W45241	24	24

(b) Lines to be monitored on visicorder.

(a)P = Peak Holder Channel.

TABLE 5-2 (continued)

Word	Instrument/Measurement	Location	Measure- ment Number	Wyle S/N	Equip. Rack to Comp. Room	F-10 Line/ Boom
61	Rocking load 8/9(1) Σ 2 901 P(a)	Section 8-9	RF09	45520,7326	58/74	58
62	Rocking load 8/9(2) Σ 2 901 P(a)	Section 8-9	RF09	7396,7	59/75	59
63	Rocking load 10/11(1) Σ 9001 P(a)	Section 10-11	RF11	7355,6	/76	
64	Rocking load 10/11(2) Σ 9001 P(a)	Section 10-11	RF11	7357,8	/77	
65	Dowel force 10/11 (Σ X) P(a)	Section 10-11	DF10	C(b)	4/78(c)	7,9,11
66	Dowel force 10/11 (Σ Z) P(a)	Section 10-11	DF10	D(d)	5/79	8,10,12
67	Rocking load B-2-2 2 901 P(a)	Base-2	RF02	45522,3	34/80	34
68	Support post (Y-2) 901A	Post X2	SPFY2	7327	60/81	60
69	Block sep. B-2-2 ECP	Base-2	BS01	W7315	35	35
70	Block sep. B-2-1 ECP	Base-2	BS01	W7312	36	36
71	Block sep. 10/11-2 ECP	Section 10-11	BS10	W7314	37(c)	37
72	Block sep. 10/11-1 ECP	Section 10-11	BS10	W7313	38	38
73	Block sep. 13/14-2 ECP	Section 13-14	BS14	W7309	39	39
74	Block sep. 13/14-1 ECP	Section 13-14	BS14	W7311	40	40
75	Top block (Y) displ. ECP	Rig. el. 14	BDY14	W7331	41	41
76	Base block (Y) displ. ECP	Rig. el. 01	BDY01	W7310	42	42
77	Base block (X) displ. LVDT	Rig. el. 01	BDX01	W45202	21	21
78	Block 7 (X) displ. LVDT	Rig. el. 07	BDX07	W45220	22	22
79	Block 3 (X) displ. LVDT	Rig. el. 03	BDX03	W45240	23	23
80	Top block (X) displ. LVDT	Rig. el. 14	BDX14	W45241	24	24

(c)= Lines to be monitored on visicorder.

(b)C = W7421, W7423, W7419

(d)D = W7435, W7420, W7418

(a)P = Peak Holder Channel

Fig. 5-2. Sine sweep and time history instrument configuration

For the shake tests, the boundary impact of the elements at levels 1, 7, and 14 was measured.

3. Dowel shear loads.

For the pluck tests, the shear loads in the dowels at the interface between elements 6 and 7 were measured in both the X and Z directions.

For the shake tests, dowel shear loads were measured at the following three locations:

- a. Between levels 13 and 14 in the X direction
- b. Between levels 10 and 14 in the X and Z directions
- c. Between levels 1 and 2 in the X direction

4. Separation and rocking of one element relative to its neighboring element.

For the pluck tests, the separation of element interfaces was measured between element levels 2 and 3, 6 and 7, and 10 and 11.

For the shake tests, separation of elements was measured between element levels 1 and 2, 10 and 11, and 13 and 14.

5. Impact load of one element rocking on its supporting element.

For the pluck tests, rocking loads were measured between elements 6 and 7.

For the shake tests rocking, loads were measured between element levels 1 and 2, 8 and 9, and 10 and 11.

5.2. INSTRUMENTATION DESIGN

In summary, the instrumentation used to measure forces and displacements in the column model was previously designed for the tests described in Refs. 3 and 4. Some of the instrumented elements in the column were taken directly from these earlier tests upon their completion, as identified in Table 4-1.

Instrumented element designs for measurement of dowel forces, rocking angles (and vertical separation), and rocking forces are illustrated in Figs. 5-3 through 5-5, respectively. A summary of the function of the instrumentation is given below, while a more complete description can be found in Refs. 3 and 4. The actual element weights are given in Table 5-3 and 5-4.

1. Dowel Force Instrumentation: Dowel shear loads were measured with strain gages attached to the dowels and oriented to pick up the bending strains resulting from the transverse load acting on the protruding end of the dowels. Each dowel contained two gages to permit load measurement in two orthogonal directions. The outputs of parallel gages on the three dowels were summed to give the net X and Z axis dowel forces on the element.
2. Block Separation and Rocking: Relative motion between elements in the Y-axis direction was measured by two eddy current probes embedded in the face of an element. In assuming that the rocking occurred about the X axis, the measured displacements were later resolved into rocking angle and uplift.
3. Rocking Force Instrumentation: The impact load between two elements in the column as a result of rocking and/or uplift was measured by an assembly of four load washers mounted in the horizontal face of one element. The load cells were summed in

Fig. 5-3. Dowel shear load instrumentation

Fig. 5-4. Element separation and rocking angle instrumentation

Fig. 5-5. Element rocking load instrumentation

TABLE 5-3
BLOCK WEIGHTS - STATIC AND PLUCK TESTS

Block Number	Block Weight (lb)	Σ Weight (lb)
14	1.08	1.08
13	2.37	3.45
12	1.18	4.63
11	2.41	7.04
10	2.29	9.33
9	2.14	11.47
8	2.12	13.59
7	2.29	15.88
6	2.24	18.12
5	2.08	20.20
4	2.12	22.32
3	1.23	23.55
2	2.44	25.99
1	2.11	28.10

TABLE 5-4
BLOCK WEIGHTS - SHAKE TESTS

Column Position	Block Number	Block Weight (1b)	Σ Weight (1b)
14	14	1.08	1.08
13	13	2.37	3.45
12	12	1.18	4.63
11	7	2.29	6.92
10	6	2.24	9.16
9	11	2.41	11.97
8	10	2.29	13.96
7	9	2.14	16.00
6	8	2.12	18.12
5	5	2.08	20.20
4	4	2.12	22.32
3	3	1.23	23.55
2	2	2.44	25.99
1	1	2.11	28.10

two pairs to record the load due to rocking in the plus and minus X-direction.

Load cells were also located at several elevations on the fixture boundary to record lateral impacts by the column in the plus and minus X direction. The outputs of a pair of load cells were summed for measurement of the total load delivered by one element in the column as depicted in the detail schematic of Fig. 5-6.

Two eddy current probes were also located on the fixture to measure the vertical displacement of the top and bottom elements of the column.

5.3. INSTRUMENT CALIBRATION

All displacement probes, dowel strain gages and load cells were calibrated prior to model testing according to Ref. 2. The calibration data for each instrument is contained in the instrument verification report of the same reference. A summary of the calibration procedures and results is presented below.

5.3.1. Eddy Current Probe Calibration

The eddy current probes assembled in the model elements were calibrated in a plus and minus rocking mode and uplift mode as shown in Figs. 5-7 and 5-8, since these were the modes of their response in the column. By resolving the displacements at the shims shown in Fig. 5-8 into gaps below each probe, calibration curves for all probes were made similar to the sample plotted in Fig. 5-9. Since the curve illustrates that the rocking angle has only a very small effect on probe output, the uplift calibration data were used in data reduction. The calibration data for all probes are contained in Ref. 2.

The eddy current probes installed on the test fixture to measure vertical displacement of the base and top elements in the column were calibrated for element uplift only.

Fig. 5-6. Boundary load cell instrumentation

Fig. 5-7. Eddy current probe pitch angle calibration configuration

Fig. 5-8. Eddy current probe uplift calibration configuration

Fig. 5-9. Calibration curve for eddy current probe number 7316, column block 10

5.3.2. Dowel Strain Gage Calibration

The strain-gaged dowels assembled in elements 1 and 10 of the model column were statically and dynamically calibrated for loads in the X and Z reference directions. The dowel gages on elements 13 of the column were not dynamically verified since this was accomplished prior to their use in the one-fifth scale dowel force test as described in Ref. 3.

All dowel strain gage calibration data are contained in Ref. 2. Static and dynamic calibration of each element was prepared as illustrated in Figs. 5-10 and 5-11. The results of these calibrations, shown in Fig. 5-12, displayed a greater sensitivity of the dowel strain gages to the dynamic loading. The phenomenon was observed earlier in the dowel force test instrument calibration and was attributed mainly to hysteretic behavior of the gage bonding material. A more complete discussion of the phenomenon is presented in Section 6.5 of Ref. 3.

Dynamic calibration of the dowel strain gages on element 10 was conducted in the same manner as those on element 1, but with the special summing circuit connected for output of the net X and Z axis dowel force. This procedure served to verify proper response of this circuit for dynamic load input.

5.3.3. Load Cell Dynamic Verification

Load cells measuring the rocking load between adjacent elements and impact loads between the elements and the fixtures were loaded dynamically prior to testing in order to verify the manufacturer's calibration constant.

The calibration data verified that the load cell output differed from the input by no more than 10% and it was therefore concluded that the manufacturer's calibration constant was verified. Since (1) repeated tests

Fig. 5-10. Dowel strain gage static calibration test configuration

Fig. 5-11. Dowel strain gage dynamic calibration test configuration

Fig. 5-12. Dowel strain gage static and dynamic calibration data

were not conducted for each particular transducer, (2) the recorded differences were within 10%, and (3) both plus and minus differences were recorded, the calibration error for the load cells was determined by computing a standard deviation using all of the recorded load cell verification data.

5.4. DATA ACQUISITION

The signal from each transducer varied in the range of 0 to 10 volts and was digitally sampled for computer tape storage by a multiplexer circuit having a period of 5 msec. Predetermined calibration factors for the instruments were subsequently used to convert the data from digital counts to engineering units. Additional electronic circuits were used to process the data from several of the 80 channels in the system. These circuits were as follows:

1. A high-frequency filter used with all LVDTs.
2. Peak holding circuits which held the peak signal from the load cells for sampling by the multiplexer, since these transducers often produced peak response in less than one multiplexer period.
3. Summing circuits used to measure the instantaneous sum of the forces on three instrumented dowels and two boundary load cells.

6. TEST PLAN

Four separate series of tests were run. They consisted of static deflection tests, column pluck tests, uniaxial sine sweep and time history tests, and biaxial sine sweep and time history tests. The details of these tests are described below.

6.1. STATIC DEFLECTION TESTS

Six tests were run applying lateral loads at specific locations along the column. The loads were applied in increments of 1 lb up to near column collapse. After each load increment, the position of each element in the column was recorded. This test series is summarized in Table 6-1.

6.2. COLUMN PLUCK TESTS

The pluck tests were designed to evaluate both free column damping and impact damping, as well as to record column impact forces under a controlled set of conditions. Both free motion and boundary impact pluck tests were run. The sequence of the pluck tests is shown in Table 6-2.

Eleven tests were run. Each test consisted of deflecting the test column laterally by pulling on it at the base of element 7 (Fig. 4-2). This was achieved with a hoop around the element and a monofilament line attached to the hoop. The column was deflected a specified distance and the line was tied off, holding the column in that position. The column's position was measured using the same procedure as in the static deflection tests except that readings were now taken at the top and bottom of each element (except for the end elements, which were restrained by the fixture). Position measurements were taken prior to lateral displacement and while the column was in the deflected condition.

TABLE 6-1
STATIC DEFLECTION TESTS

Test Sequence	Load Elevation By Block No.	Load Direction	Top Block Gap (in.)
1	4/5	-X	-X0, +X0.5
2	Both 6/7 and 3/4	-X +X	-X0, +X0.5
3	Both 6/7 and 3/4	+X -X	+X0, -X0.5
4	4/5	+X	+X0, -X0.5
Adjust left (+X) side top block to 8.47 in. from the right fixture column.			
Rotate the fuel element column 90 deg clockwise.			
5	4/5	+X	+X0, -X0.50
6	4/5	-X	-X0, +X0.50

TABLE 6-2
COLUMN PLUCK TESTS

Test Sequence	Initial Displacement (in.)	Right Side (-X) Boundary Gap	Pull Point Block Number
1	0.10	1.0	7
2	0.25	1.0	7
3	0.50	1.0	7
4	1.00	1.0	7
Adjust right side boundary (-X).			
5	0.50	0.1	7
6	1.00	0.1	7
Oscillograph recording for the remaining test in this table			
7	0.75	0.1	7
8	Adjust number seven block boundary 0.005 in. toward the negative X boundary (all other parameters same as for test 6).		
9	Adjust number seven block boundary 0.010 in. toward the positive X boundary (all other parameters the same as for test 6).		
10	1.00	0.05	7
11	1.00	0.0	7

With the column in the deflected position, the instrumentation was turned on and the column was released by cutting the monofilament line.

In Tests 1 through 4 the column remained in a state of free motion, since the boundaries were backed away far enough to insure that no impact would occur. In Tests 5 and 6, boundary impact was forced by setting the boundary gap to 0.10 in., which was less than the overtravel measured in the free motion tests.

Test 7 was run to provide a data point between the data of Test 5 and Test 6. Tests 8 and 9 were run to study the effect of a boundary that had the supports slightly displaced relative to each other. Tests 10 and 11 were run to study the effect of varying the boundary gap. Only oscillograph data was recorded in Tests 7 through 11.

6.3. UNIAXIAL SINE SWEEP TESTS

A total of 17 tests were performed in this category as given in Table 6-3. For the tests where the excitation was along the horizontal axis (X-axis), the sweep rate was 0.5 decades per minute in the range of 1.5-30-1.5 Hz (sweep up and down). For the tests having vertical excitation (Z-axis) the sweep rate was 0.5 decades per minute in the range of 1.5-50-1.5 Hz. These frequency ranges were based on preliminary calculations showing the first three bending modes of the column to be within 30 Hz and the fundamental axial mode of the column to be approximately 29 Hz.

The purpose of the first six tests in this category was to demonstrate that:

1. Test rig rotation in a horizontal plane during a horizontal sine sweep was small. This was determined from horizontal accelerometer data measured at the base and top of the rig. Agreement to within 5% was arbitrarily assumed as an acceptance criterion.

TABLE 6-3
UNIAXIAL SINE SWEEP TESTS

Test No.	Axis	G-Level	Boundary Gap (in.)	Top Block ^(a) Gap (in.)	Bottom Block ^(a) Gap (in.)
1	Horiz.	0.5	0.0 locked	0.0 locked	0.0 locked
	Input motion will consist of a sine sweep from 1.5 to 30 to 1.5 Hz at 0.5 decades per minute.				
2	Horiz.	0.25	0.10	0.10	0.10
	Input motion will consist of a sine sweep from 1.5 to 30 to 1.5 Hz at 0.5 decades per minute.				
3	Horiz.	0.25	0.10	0.10	0.10
	Rotate the column 180 deg on its support spring posts and repeat the sine sweep from 1.5 to 30 to 1.5 Hz at 0.5 decades per minute.				
4	Vert.	0.25	0.10	0.0	0.0
	Rotate the column back 180 deg on its support spring posts and conduct the sine sweep from 1.5 to 50 to 1.5 Hz at 0.5 decades per minute.				
	Attach the LVDTs to the graphite fuel element blocks.				
5	Vert.	0.25	0.10	0.0	0.0
	Input motion will consist of a sine sweep from 1.5 to 50 to 1.5 Hz at 0.5 decades per minute.				
6	Horiz.	0.25	0.10	0.10	0.10
	Input motion will consist of a sine sweep from 1.5 to 30 to 1.5 Hz at 0.5 decades per minute.				
	Submit an instrumentation verification report to GAC.				

TABLE 6-3 (continued)

Test No.	Axis	G-Level	Boundary Gap (in.)	Top Block ^(a) Gap (in.)	Bottom Block ^(a) Gap (in.)
7	Horiz.	Exploratory	1.00	0.0	0.0 locked
	Adjust the column boundary as indicated. Conduct a number of sine sweeps from 1.5 to 30 to 1.5 Hz, increasing input g level until the level is reached where the fuel element column has maximum response without contacting the boundary. Determine the natural frequencies of the column during these trials. Oscillograph recording will be used for trial runs. The final sweep will utilize the computer for data acquisition.				
8	Horiz.	Same as No. 7 final	1.00	0.0	0.0 locked
Altered - see text	Determine the first column natural frequency from oscillograph records of Test 7. Conduct a sine sweep (at constant g level) up to the first natural frequency and cause a quick shutdown to take place for column damping.				
9	Horiz.	Same as No. 7 final	1.00	0.0	0.0 locked
Altered - see text	Repeat Test 8 only use the second natural frequency determined from Test 7.				
10	Horiz.	Same as No. 7 final	1.00	0.0	0.0 locked
Altered - see text	Repeat Test 8 only use the third natural frequency determined from Test 7.				

TABLE 6-3 (continued)

Test No.	Axis	G-Level	Boundary Gap (in.)	Top Block ^(a) Gap (in.)	Bottom Block ^(a) Gap (in.)
11	Horiz.	Exploratory	1.00	0.0	0.0 locked
	Rotate the fuel element column 90 deg so that excitation is across the fuel element corners. Conduct a number of sine sweeps from 1.5 to 30 to 1.5 Hz, increasing the input g level until the level is reached where the fuel element column has maximum response without contacting the boundary. Determine the natural frequencies of the column during these trials. Oscillograph recording will be used for trial runs. The final sweep will utilize the computer data acquisition. Rotate the column 90 deg back to its original position.				
12	Horiz.	0.25	0.10	0.0	0.0 locked
	Input motion will consist of a sine sweep from 1.5 to 30 to 1.5 Hz at 0.5 decades per minute.				
13	Horiz.	0.50	0.10	0.0	0.0 locked
	Input motion same as Test 12.				
14	Horiz.	0.50	0.40	0.0	0.0 locked
	Input motion same as Test 12.				
15	Horiz.	0.50	0.40	0.40	0.2
	Input motion same as Test 12.				
16	Vert.	0.25	0.10	0.0	0.0 locked
	Input motion will consist of a sine sweep from 1.5 to 50 to 1.5 Hz at 0.5 decades per minute.				

TABLE 6-3 (continued)

Test No.	Axis	G-Level	Boundary Gap (in.)	Top Block ^(a) Gap (in.)	Bottom Block ^(a) Gap (in.)
17	Vert.	0.50	0.10	0.0	0.0 unlocked Input motion will consist of a sine sweep from 1.5 to 50 to 1.5 Hz at 0.5 decades per minute. Dismantle the column and visually inspect the fuel elements and the instrumentation.

^(a) Free to slide vertically except where locked.

2. Instrument wiring to the column did not affect instrument response.
3. The column vibrated about its centerline.

Compliance with the rig rotation requirement of (1) above became a formidable task since the test rig initially was placed on top of the shaker table. In addition to excessive rotation during horizontal motion, initial vertical sine sweep tests revealed an oil column resonance in the vertical shaker system which resulted in large rotations of the test rig at approximately 36 Hz.

The rig rotation problems were eliminated by a redesign of the rig support scheme as illustrated in Figs. 4-3 and 4-4. In this redesign the test rig was sunk into the shaker table. This activity and the results of the follow-on rotational verification tests are documented in Ref. 2.

The purpose of Tests 7 and 11 was to identify the first three bending (with no boundary impact) and axial resonance modes of the column. However, only the first mode was identified in each case of horizontal and vertical testing.

Tests 8, 9, and 10 were designed to measure the horizontal transient column decay motion by performing a sinusoidal sweep up to the resonance frequency and subsequent instantaneous arrest of the rig motion. Since only one mode was identified, these tests were modified to measure the decay motion of this mode at the three input g-levels given below:

1. Test 8; shutdown at 4.5 Hz and 0.03 g.
2. Test 9; shutdown at 3.8 Hz and 0.04 g.
3. Test 10; shutdown at 1.4 Hz and 0.05 g.

The purpose of Tests 12 through 17 was to obtain data to study the influence of the following parameters on the column response.

1. Input g-level.
2. Boundary gap.
3. End constraints.

6.4. UNIAXIAL TIME HISTORY TESTS

All time history tests in the program were performed using the General Atomic Company design earthquake generated for soft soil and 5.0% structural damping. The time history represented NRC design spectrum criteria consistent with Reg. Guide 1.60, December 1973, and was generated for a 3000-MW(t) HTGR plant at an elevation corresponding to mid-height. A vertical time history with the same parameters but corresponding to the core support floor elevation was applied to the column in the vertical direction. Each shock was to a one-fifth scale in magnitude and time according to the scaling relationships:

$$X_{\text{model}} = 1/5 X_{\text{prototype}}$$

$$t_{\text{model}} = \sqrt{5} t_{\text{prototype}}$$

The boundary gaps and column end constraints for each test in this category appear in Table 6-4. The horizontal and vertical input motions are shown in Figs. 6-1 and 6-2.

6.5. BIAXIAL SINE SWEEP TESTS

The biaxial sine sweep tests were performed to study simultaneous horizontal and vertical excitation and the effect of phase lag between the two input waveforms on the response of the column.

The phase angle was varied from 0 to 90 deg in Tests 23 through 27 to determine the phase angle producing the largest column response. The tests were then repeated at this phase angle for several in g-levels and column-end constraints as shown in Table 6-5.

Fig. 6-1. Horizontal time history excitation, shock 4, g-ground

Fig. 6-2. Vertical time history excitation, shock 4, g-ground

TABLE 6-4
UNIAXIAL TIME HISTORY TESTS

Test No.	G-Level (g)	Boundary Gap (in.)	Top Block ^(a) Gap (in.)	Bottom Block ^(a) Gap (in.)	Comments
Horizontal axis					
18	0.50	0.10	0.0	0.0	Base block locked
19	0.50	0.25	0.0	0.0	Base block locked
20	0.50	0.25	0.0	0.125	
Vertical axis					
21	0.50	0.25	0.0	0.0	Base block locked
22	0.50	0.25	0.0	0.0	Base block unlocked

(a) Free to slide vertically except where locked (maximum gap = 0.005 in.)

TABLE 6-5
BIAXIAL SINE SWEEP TESTS^(a)

Test No.	G-Level		Boundary Gap (in.)	Top Block Gap (in.)	Bottom Block Gap (in.)	Phase Angle (deg)
	Horiz.	Vert.				
23	0.50	0.25	0.2	0.0	0.0 locked	0
24	0.50	0.25	0.2	0.0	0.0 unlocked	0
25	0.50	0.25	0.2	0.0	0.0 locked	22.5
26	0.50	0.25	0.2	0.0	0.0 locked	45.0
27	0.50	0.25	0.2	0.0	0.0 locked	90.0
28	0.50	0.50	0.2	0.0	0.0 locked	0
29	0.50	0.25	0.2	0.2	0.1 unlocked	0
(b)						

(a) Sine sweeps to be 1.5-50-1.5 Hz at 0.5 decades/minute.

(b) Dismantle column and inspect blocks and block instrumentation.

6.6. BIAXIAL TIME HISTORY TESTS

The biaxial time history tests were run to study the column response to simultaneous horizontal and vertical earthquake motion. Nine tests were run and are described in Table 6-6. In-phase excitation and two tests with time lags between the horizontal and vertical rig inputs were run. The time lag tests corresponded to the maximum positive and negative cross correlation factor for the two waveforms, respectively.

TABLE 6-6
BIAXIAL TIME HISTORY TESTS

Test No.	G-Level		Boundary Gap (in.)	Top Block Gap (in.)	Bottom Block Gap (in.)	Time Lag (sec)	Comments
	Vert.	Horiz.					
30	0.25	0.50	0.10	0.0	0.0	0.0	Base block locked
31	0.25	0.50	0.10	0.0	0.0	0.18	Base block locked
32	0.25	0.50	0.10	0.0	0.0	1.17	Base block locked
33	0.25	0.50	0.10	0.0	0.0	0.0	Base block unlocked
34	0.25	0.50	0.25	0.0	0.0	0.0	Base block unlocked
35	0.25	0.50	0.25	0.0	0.125	0.0	Base block unlocked
36	0.25	0.50	0.25	0.25	0.125	0.0	Base block unlocked
37	0.50	0.75	0.25	0.25	0.125	0.0	Base block unlocked
38	0.50	0.50	0.25	0.25	0.125	0.0	Base block unlocked

7. DATA REDUCTION

An array of computer programs was used to process the digitized data into special formats of engineering units. With the exception of subroutine ANGLE Z and program VIEWC, they are the same programs used to reduce the 1/5-scale dowel force test data.

Subroutine ANGLES in the dowel force test data reduction plan was replaced by ANGLZ, since only two eddy current probe measurements per block interface were used to determine rocking angle and uplift in the column tests, as opposed to three probes in the dowel force test which provided data for calculating rocking orientation as well.

Computer program VIEWC contains subroutine ANGLZ for output printout and S-C 4020 plots of time history data. The computer card decks for programs ANGLE and MAIN are located in storage with the raw data tapes and computer output. Listings of programs ANGLE and MAIN are given in Ref. 5.

8. TEST RESULTS

The test program produced over 143 million data points which were stored on the magnetic tapes. Only the most relevant data for code correlation were reduced and appear in this section of the report and in Ref. 6.

8.1. STATIC DEFLECTION TESTS

Static deflections were imposed on the column by the application of horizontal loads or moments as shown in Fig. 4-2. The deflected column configuration for a horizontal load and a moment are shown in Figs. 8-1 and 8-2, respectively. Similar data for the remaining static tests are included in Ref. 6.

8.2. COLUMN PLUCK TESTS

The test parameters for the column pluck test were the column initial deflected shape and magnitude and nominal gap between the boundary and the undeflected column. The test results consisted of the time history response of the transducers in the column elements as well as those on the boundary.

Typical free vibration column test data without the column hitting the support boundary were obtained for a column initial deflection of 0.10 in. at the column midheight, Fig. 8-3. The deflection time history for block 7, and rocking angle response for blocks 10 and 11, are shown in Figs. 8-4 and 8-5. By calculating the log decrement from Fig. 8-4, the estimated damping ratio was 15% of critical. Since the column was in a "clamped" configuration at top and bottom ends, the vibration mode was that of the

Fig. 8-1. Column deflection under horizontal load, static test 4

Fig. 8-2. Column deflection under in-plane moment, status test 2

Fig. 8-3. Column initial deflection for pluck test 1

Fig. 8-4. Horizontal displacement time history response of element for pluck test 1

Fig. 8-5. Rocking angle time history response of elements 10 and 11 for pluck test 1

fundamental beam mode. The associated resonance frequency was 3.5 Hz. Both damping and resonance frequency decreased with increasing displacement magnitudes as shown in Fig. 8-6. The frequency response indicated that the free column structure is representative of a spring-softening system.

8.3. UNIAXIAL SINE SWEEP TEST RESULTS

The test parameters for the horizontal and vertical uniaxial sine sweep tests 12, 15, 16, and 17 are given in Table 6-3. In horizontal excitation of the column, the elements impacted the boundary supports. In this mode, the vibration resonance frequency tends to increase with an increase in the excitation g-level. This is characteristic of a nonlinear spring-hardening system. The phenomenon is illustrated by the dowel force response in Figs. 8-7 and 8-8, where the resonance frequency shifted from 6.4 Hz to 8.8 Hz for a horizontal input g-level increase of 0.25 g. Thus, the vibration of a column with side restraints has different characteristics compared with those of a free column as discussed in Section 8.2.

The column frequency response to sinusoidal excitation at 0.5 g in the vertical direction with support posts active is shown in Fig. 8-9. The resonance frequency shown at approximately 29 Hz is represented by the support posts. This was verified by calculation considering the column as a lumped mass attached to a spring having a stiffness equivalent to that of the support posts. The critical resonance also shows typical nonlinear characteristics with the sharp drop-off in response on the low frequency side of the peak as shown in Figs. 8-9 and 8-10. This response behavior is indicative of a spring softening system. In test 16, no vertical resonance of the column was obtained when the base block of the column was locked, rendering the support posts inactive.

8.4. ANALYSIS OF THE TEST RIG AND SHAKER TABLE FREQUENCY RESPONSE

In order to determine the actual input to the model, the response of the X and Y-axis accelerometers located on the shaker table and test rig

Fig. 8-6. Column damping and resonance frequency as a function of displacement magnitude

Fig. 8-7. X-axis dowel force response to a horizontal sine sweep, test 12, element 10

Fig. 8-8. X-axis dowel force response to a horizontal sine sweep, test 13, element 10

Fig. 8-9. Vertical resonance - sweep up, 0.5g fixture acceleration

Fig. 8-10. Vertical resonance - sweep down, 0.5g fixture acceleration

was recorded. The response from these instruments should agree with that specified in Ref. 1. From this investigation it was determined that

1. Shaker table resonances are determined from horizontal cross-coupling during vertical excitation and are present at 17 and 34 Hz. These are identified with the aid of Fig. 8-11. The cause of the remaining peaks is not clearly understood but could have been caused by the loosening effect of one or several mono-ball joints in the structure.
2. A likely oil column resonance was present in the vertical shaker system at 17 Hz.
3. An oil column resonance in the horizontal shaker system existed in the region of 5.2 and 6.2 Hz.
4. No vertical cross-coupling during horizontal excitation was present below 10 Hz. Since horizontal frequency data above 10 Hz were not analyzed, cross coupling above this frequency is unknown.

The nominal rig input g-level was shown by the rig accelerometer data to be within test specification criteria, although variations about the nominal were present which contributed to the random error of the response. This is discussed in Section 9.0.

8.5. BIAXIAL SINE SWEEP TESTS

Data were reduced for the column response to biaxial sine sweep tests 23 and 24 having the nominal parameters specified in Table 6-5. Resonance plots similar to those obtained for uniaxial excitation showed horizontal and vertical column resonances at exactly the same frequency values for identical excitation g-levels and column gaps. As illustrated in Fig. 8-12, the support post frequency response for Test 24, with an unlocked base block, gives the fundamental vertical column resonance as 29 Hz.

Fig. 8-11. Test rig base x-axis acceleration frequency response, test 17, 10 to 40 Hz

Fig. 8-12. Column support post frequency response to biaxial excitation, test 24

8.6. UNIAXIAL TIME HISTORY TESTS

Uniaxial horizontal and vertical time history tests were performed using the rig inputs previously shown in Figs. 6-1 and 6-2. Support post load and column element rocking angle, uplift, rocking force, and dowel force are shown in Figs. 8-13 through 8-22 for horizontal and vertical tests 20 and 22. The remaining uniaxial time history data were included in Ref. 6. The parameters of Tests 20 and 22 are shown in Table 6-4.

The column support forces shown in Figs. 8-13 and 8-14 illustrate that the overall load for pure horizontal excitation is approximately twice that for vertical excitation. The existence of a 0.125-in. base block (core support floor block) gap in the horizontal time history test, therefore, seems to present a severe local load environment for the posts.

The rocking angle, uplift, rocking force, and dowel force response shown in Figs. 8-15 through 8-18 illustrate a negligible response to a vertical input, except for the inadvertently high starting transient of the waveform which was artificially imposed. This is in contrast to the significant response shown in Figs. 8-19 through 8-22 for a horizontal input. Thus it appears that element rocking and boundary collisions during horizontal excitation present a generally more severe loading environment than a purely vertical input to the column.

8.7. BIAXIAL TIME HISTORY TESTS

Simultaneous horizontal and vertical time history tests were performed according to Table 6-6 for a range of test parameters including input excitation phase lag, column gaps, and excitation g-level. The typical response of element rocking angles, support post forces, element lateral impact forces, and rocking forces are shown in Figs. 8-23 through 8-27 for Test 35. This test represents a 0.25/0.5-g (vertical/horizontal) ground acceleration input, zero phase lag, and column gaps of 0.25/0.0/0.125 in. (mid-column/plenum element/support block).

Fig. 8-13. Time history response of column support post pair 1, test 20

Fig. 8-14. Time history response of column support post pair 1, test 22

Fig. 8-15. Elements 13/14 rocking angle time history response, test 22

Fig. 8-16. Elements 13/14 uplift time history response, test 22

Fig. 8-17. Elements 10/11 rocking force time history response, pair 1, test 22

Fig. 8-18. Elements 10/11 x-axis dowel force time history response, test 22

Fig. 8-19. Elements 13/14 rocking angle time history response, test 20

Fig. 8-20. Elements 13/14 uplift time history response, test 20

Fig. 8-21. Elements 10/11 rocking force time history response, pair 1, test 20

Fig. 8-22. Elements 10/11 x-axis dowel force time history response, test 20

Fig. 8-23. Time history response of column support post pair 1, test 35

Fig. 8-24. Elements 10/11 x-axis dowel force time history response, test 35

Fig. 8-25. Elements 13/14 rocking angle time history response, test 35

Fig. 8-26. Elements 13/14 uplift time history response, test 35

Fig. 8-27. Elements 10/11 rocking force time history response, test 35

A summary of the column response to Tests 30, 32, 35, 37, and 38 are given in Table 8-1. The comparison between Tests 30 and 32 illustrates the effect of introducing a phase lag between horizontal and vertical input. Little effect on the response parameters is observed except for the element impact forces at midheight, which decrease considerably. At other locations along the column, insignificant change in impact forces was noted. By increasing the g-level of the vertical input from 0.25 to 0.5 g, comparing Tests 35 and 38, the support post load and rocking forces are shown to increase by approximately 75% and 40%, respectively. Little change was observed in the dowel force and impact force parameters. From these observations, the following may be concluded:

1. Maximum column response occurs for two-axis horizontal and vertical input applied in-phase.
2. The vertical input has little effect on lateral column response parameters such as element impact forces and dowel forces.

Increasing the column gap has a large effect, as expected, on element lateral impact forces and dowel forces, although rocking force and support post loads remain virtually unchanged. This is demonstrated from Tests 33 and 35.

Comparing Tests 38 and 37, it is seen that an increase in horizontal g-level increases all column response parameters. The element lateral impact forces essentially double as a result of increasing the g-level from 0.5 to 0.75 g.

TABLE 8-1
MAXIMUM COLUMN RESPONSE (LB) TO BIAXIAL TIME HISTORY TESTS

Test No.	Support Post Load [(y-1)+(y-2)]	Dowel Force (Block 10/11)	Impact Force (Mid-height)	Rocking Force (Block 10/11)	Change in Boundary Conditions(a)
30	--	56.0	160	89.0	0.25/0.5 g ^(b) 0.1/0.0/1.0(c) in. gap 0.0 sec phase lag Base block locked
32	--	58.0	110	90	1.17 sec phase lag
33	21.5	45.0	180	92.5	Base block unlocked
35	21.0	60.0	265	90.0	0.25/0.0/0.125 in. gap
38	37.5	54.0	265	127	0.5/0.5 g 0.25/0.25/0.125 in. gap
37	47.0	60.0	>400 ^(d)	145	0.5/0.75 g 0.25/0.25/0.125 in. gap

(a) Refer to Table 6-6.

(b) Vertical/horizontal.

(c) Mid-column/plenum block/support block.

(d) Instrument saturated.

9. ERROR ANALYSIS

9.1. ERROR CALCULATION

Statistical error in the test data was determined by the component error analysis outlined in Section 10.0 of Ref. 3, since no repeated tests were performed in the program. The standard deviation of the instrument response, U_R , is given by the following equation using appropriate values for the component deviations S_{G_c} , S_{N_R} ,

$$\hat{S}_{U_R} = \frac{S_{U_R}}{\bar{U}_R} = \left\{ \hat{S}_{G_c}^2 + \hat{S}_{G_p}^2 + \hat{S}_{G_s}^2 + \hat{S}_{N_R}^2 + \left[\frac{g}{\bar{U}_R} \frac{\delta U_M}{\delta g} (f, g) \right]^2 \hat{S}_g^2 + \left[\frac{f}{\bar{U}_R} \frac{\delta U_M}{\delta f} (f, g) \right]^2 \hat{S}_f^2 + \hat{S}_{G_v}^2 + \hat{S}_{G_G}^2 \right\}^{1/2} \quad (9-1)$$

The first four components S_{G_c} , S_{G_p} , S_{G_s} , and S_{N_R} in the equation represent deviations in digitization, signal peak holding, signal summation, and extraneous conditions. These were known from previous error analyses to be relatively insignificant.

The error components representing deviations due to input frequency, S_f , and instrument calibration, S_{G_v} , were taken from the dowel force test, since similar test hardware and instrumentation were used in the column shake test.

The biaxial shaker system exhibited horizontal cross-coupling during vertical input at 17 Hz and 34 Hz, and an oil column resonance during

horizontal excitation at 5.8 Hz. Therefore, the data at these particular frequencies were considered to contain an indeterminate error.

Examination of the data output from the accelerometers attached to the shaker table and test rig revealed that control of the biaxial shaker system was less precise than that for the uniaxial system used in the 1/5-scale dowel force test. The one standard deviation of the g-level, $\hat{S}_g$, was estimated at 2.5% as compared with a 1.0% to 1.8% deviation in the dowel force test.

The remaining term in the equation, S_{G_c} , represents the effect of geometry variations on the instrument response. The only data available to estimate this deviation were generated by analysis and are illustrated in Fig. 9-1. The data in the figure show that varying the local boundary gap by 0.015 in. results in a load increase of 66 lb, or gives a nominal rate of 4400 lb per in. Considering the model element dowel (and socket) alignment tolerance of ± 0.002 in., the dowel load measurement at elevation 10/11 in the column could vary by about 12.3 lb. (This value was considered to be a two-sigma variation.)

Hence, for a nominal dowel force of 30 lb at elevation 10/11, the one-sigma geometry deviation was approximately 20%. This value was considered relatively large for a geometry error; however, it reflects the high sensitivity of the load where spring rates of the impacting surfaces are very large. For this reason, the rate of 4400 lb per in. was adopted for boundary impact load and rocking load as well to compute statistical geometry errors. Using a nominal load measurement in an 0.5-g sine sweep near elevation 10/11 in the column, the resulting estimates for geometry errors in the instruments are given in Table 9-1. Other errors in the table were based on the 1/5-scale dowel force test for similar instruments. Table 9-2 gives the total one-sigma statistical error in the response data represented by Eq. 9-1.

Fig. 9-1. Maximum dowel shear force versus boundary gap, 1/5 scale single column shake test analysis

TABLE 9-1
COLUMN SHAKE TEST INSTRUMENT COMPONENT ERRORS

Component Error ^(a)	Dowel Strain Gages	Load Cells	Eddy Current Probes
$\frac{g}{u_R} \frac{du_M}{dg} \hat{S}_g$	8.3	11	2.5
$\frac{f}{u_R} \frac{du_M}{df} \hat{S}_f$	0	0	0
$\hat{S}_{G_C}$	0.025	0.025	0.025
$\hat{S}_{N_R}$	0.5	3.0	1.5
$\hat{S}_{g_{TH}}$	2.5	2.5	2.5
$\hat{S}_f$	0	0	0
$\hat{S}_{G_P}$	0.5	0.5	0.5
$\hat{S}_{G_S}$	0.5	0.5	0.5
$\hat{S}_{G_V}$	9	6	7.5
$\hat{S}_{G_G}$	20	8	1
$\frac{du_M}{dg}$	900	2000	0.2

(a) Fractional one-sigma errors expressed in percent.

TABLE 9-2
COLUMN SHAKE TEST TOTAL INSTRUMENT DATA ERRORS

Instrument	1 σ Random Error (%)
Rocking angle	8.0
Uplift	8.0
Dowel shear force	23.0
Rocking forces	15.0
Lateral support loads	15.0

9.2. ROCKING ANGLE AND UPLIFT STATISTICAL ERROR

Rocking angle and uplift statistical error was computed from the eddy current statistical errors using the equations from Ref. 3:

$$\hat{S}_{\theta} = \left[\sum_{i=1}^2 \left(\frac{\delta \theta}{\delta z_i} \hat{S}_{Z_i} \right)^2 \right]^{1/2} \quad (9-2)$$

and

$$\hat{S}_{\Delta} = \left[\sum_{i=1}^2 \left(\frac{\delta \Delta}{\delta z_i} S_{Z_i} \right)^2 \right]^{1/2} \quad (9-3)$$

where Z is the element vertical displacement and where the rocking angle, θ , is given by

$$\theta = \arctan \frac{(Z_1 - Z_2)}{b} \quad (b = 1.56 \text{ in.}) \quad (9-4)$$

and the uplift, Δ is given by

$$\Delta = Z_2 - 1.34 | \tan \theta | \quad (9-5)$$

Performing the differentiation in Eqs. 9-2 and 9-3 yields the final equations:

$$\hat{S}_{\theta} \approx S_{Z_1} (= \hat{S}_{Z_2}) \quad (9-6)$$

$$\hat{S}_{\Delta} \approx S_{Z_1} (= \hat{S}_{Z_2}) \quad .$$

10. REFERENCES

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